Nucleon Elastic Form Factors:
An Experimentalist's Perspective

Glen Warren

Battelle

& Jefferson Lab

Division of Nuclear Physics

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Outline:

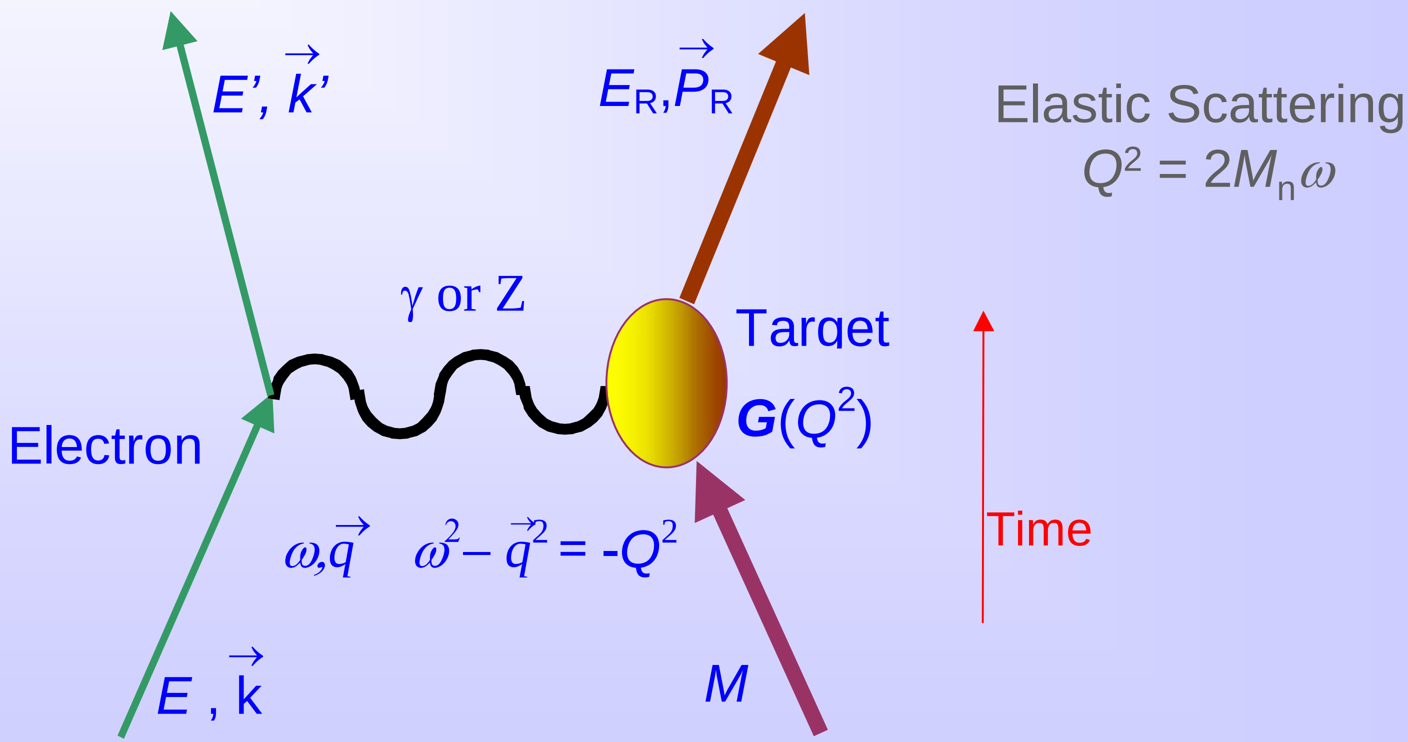
- The Fib and the Questions
- EM FF
- Strangeness

First, I'm going to fib

- This mini-symposium is titled "Progress in Nucleon Form Factors".
- To recognize the "progress" we must know from where we came.
- I will first present the classic introduction to nucleon form factors. It would have raised few eyebrows even as little as 5 years ago.
- Listen, learn if you need to, *but do not think this is the whole truth*.

Form Factors

Structure of particles described by form factors.



Form factors hide our ignorance of how the composite particle is constructed.

Interpretation of Form Factors

In non-relativistic limit, form factors are Fourier transforms of distributions:

$$G_E(\vec{q}) = \int \rho_{ch}(r) \exp(i\vec{q}\cdot\vec{r})\, d^3r$$

Spin $^1/_2$ particles have two elastic electromagnetic form factors:

G_E : electric form factor
G_M : magnetic form factor

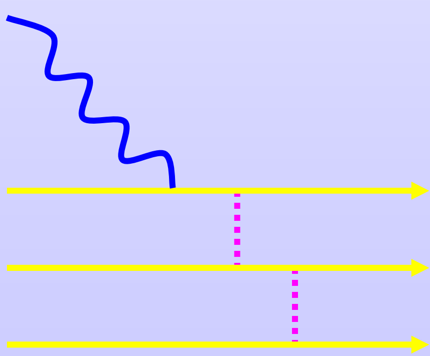
OR

F_1 : Dirac form factor
F_2 : Pauli form factor

$G_E = F_1 - \tau F_2$ and $G_M = F_1 + F_2$

pQCD

- At low Q^2, forced to use effective theories.
- At high Q^2, use pQCD, which relies on quark helicity conservation.
- pQCD predicts asymptotic behavior for F_1 and F_2 following "counting rules."



- For elastic scattering in one photon exchange, quarks must exchange two gluons to distribute momentum to remain a nucleon
  - $F_1 \sim 1/Q^4$
- F_2 requires an additional spin flip:
  - $F_2 \sim F_1/Q^2 \sim 1/Q^6$
- Expect in pQCD regime:
  - $Q^2\ F_2/F_1 \sim$ constant
  - or $G_E/G_M \sim$ constant

Seeds of Doubt ...

Interpretation of form factors as distributions requires:

- non-relativisitic limit,
  - data exists well into the relativistic region.
- or, if relativistic, there is no energy transferred (Breit frame)
  - a "physical" property for an unphysical reference frame?

- *To think that the form factors are intimately connected to charge and magnetic distributions is simplistic and may lead to physical misinterpretation of the experimental results.*

Dipole Form Factor

G_{Ep}, G_{Mp} and G_{Mn} roughly follow the Dipole Form Factor.

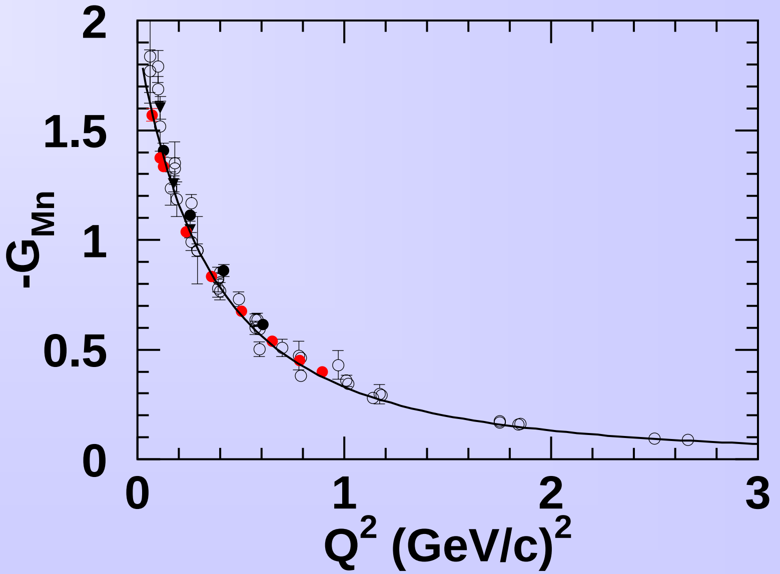
$$G_D \equiv \left(1 + Q^2/0.71\right)^{-2}$$

The 0.71 is determined from a fit to the world's data.

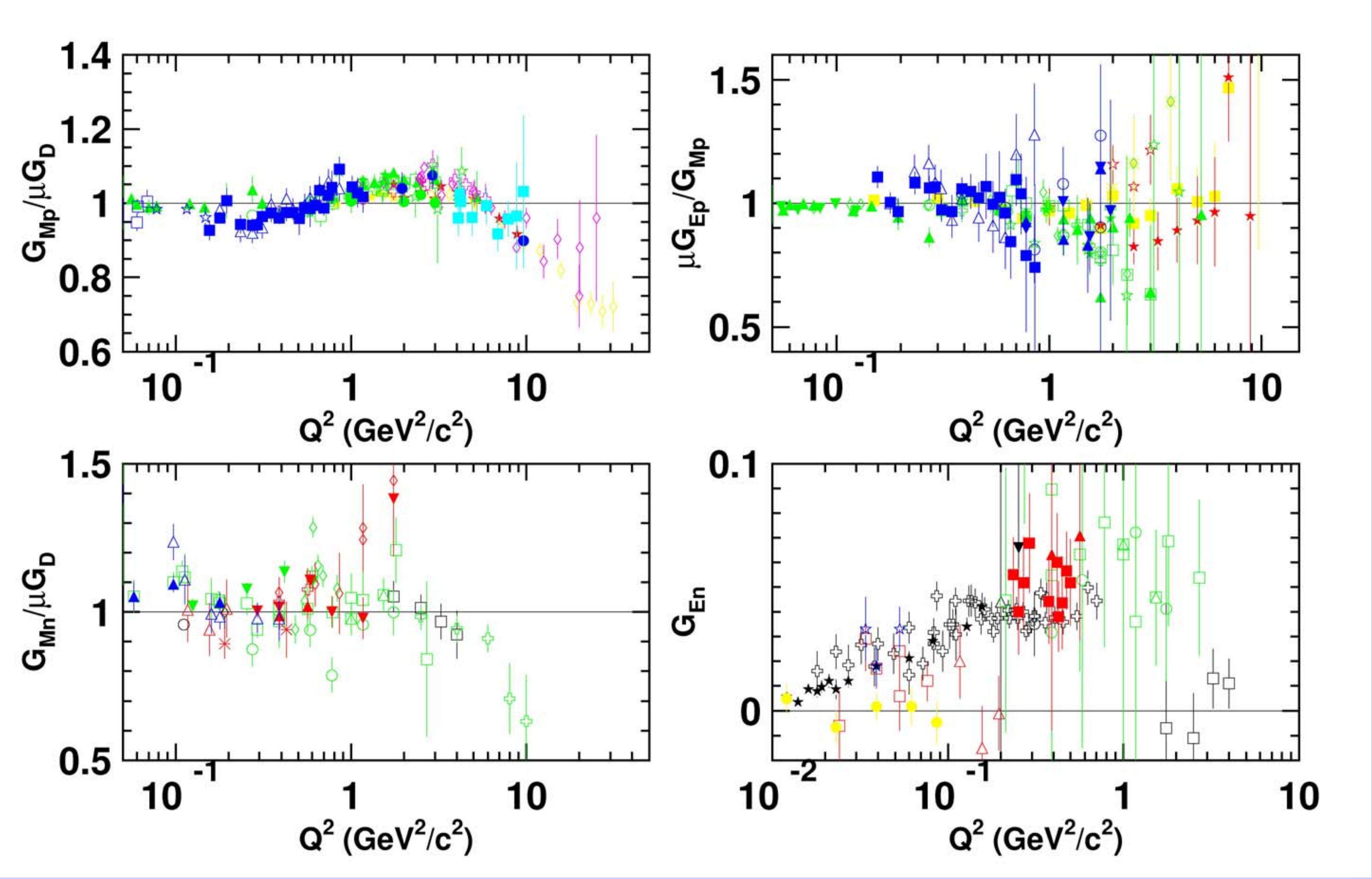
An Exponential distribution has dipole form factor:

For Example:

$$G_{Mn} \cong \mu_n G_D$$



“World” Data up to 1997



G_{Mn} Results

Two Modern Methods:

1) Ratio of Cross sections

measure $\dfrac{\sigma(D(e,e'n))}{\sigma(D(e,e'p))}$

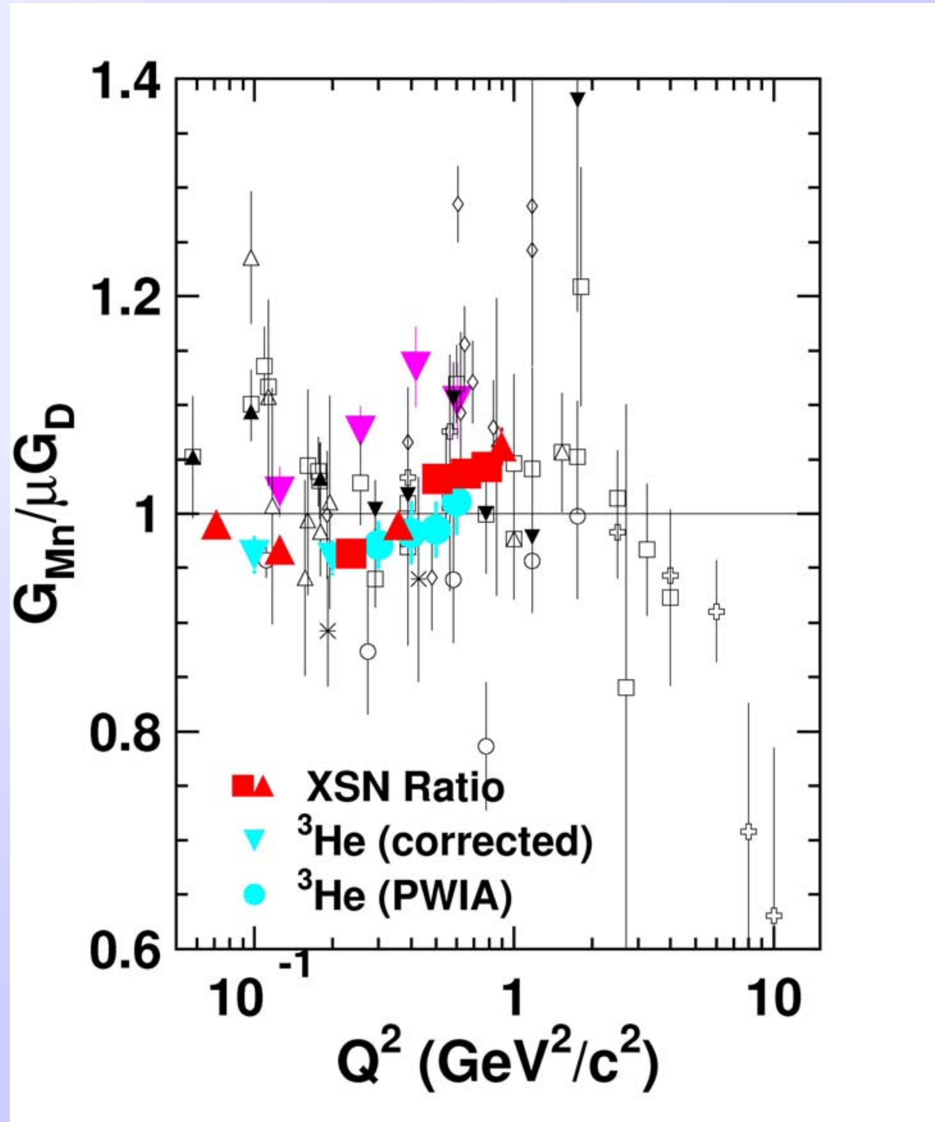
Difficulty is absolute neutron detection efficiency

2) Beam-Target Asymmetries

$$A \propto \frac{G_{Mn}^2}{1 + aG_{Mn}^2}$$

where $aG_{Mn}^2 \ll 1$

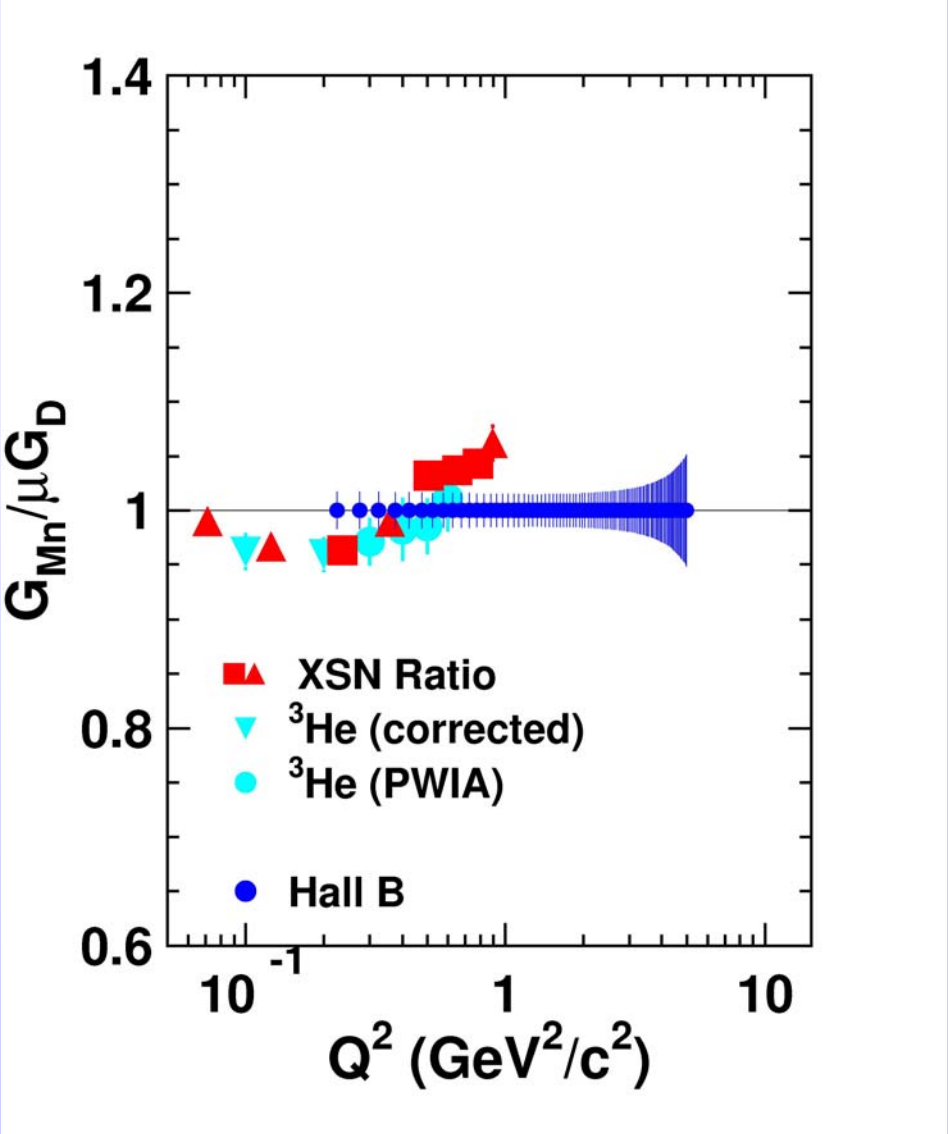
Difficulty is nuclear corrections



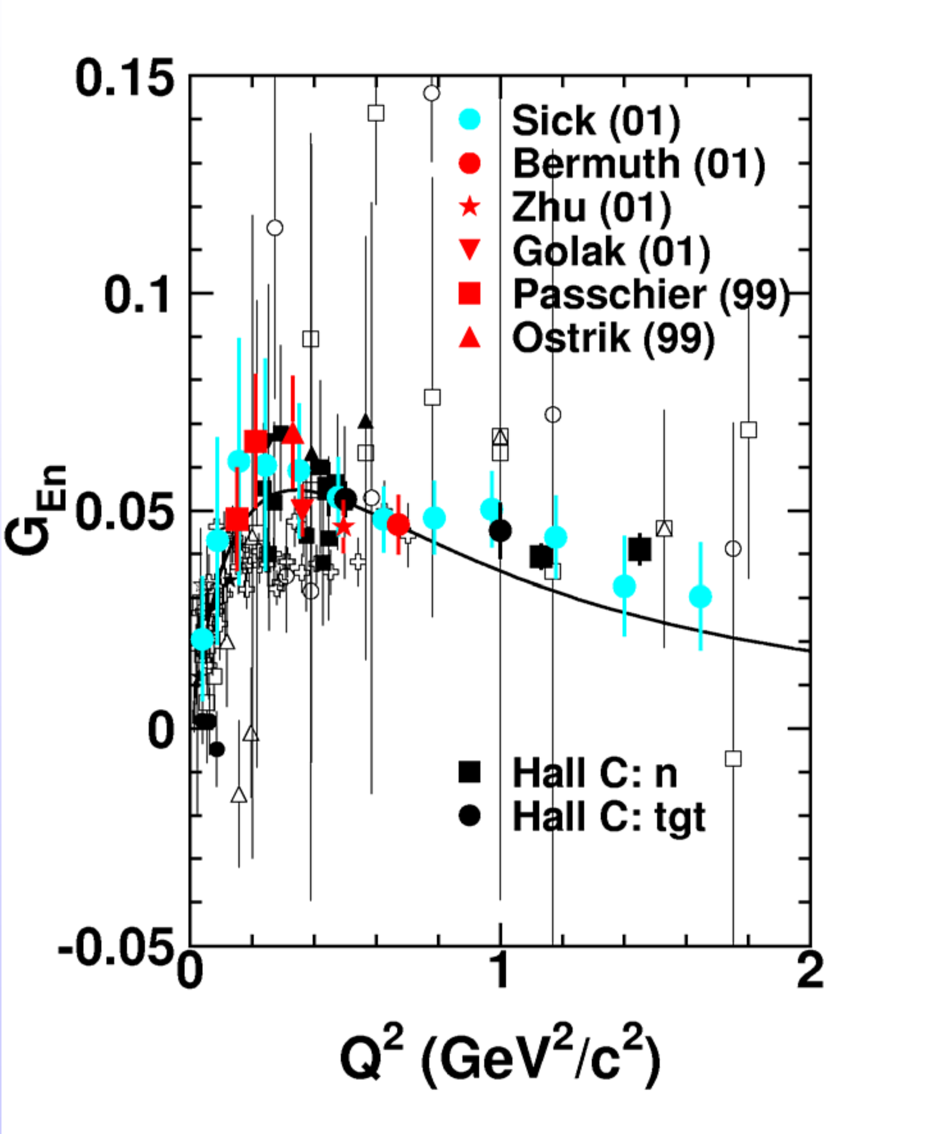
G_{Mn} Future

Hall B has taken data using ratio of cross sections method: a talk on this experiment will be presented in this session.

Error bars are for uniform bins in Q^2. Could increase bin size to reduce errors at large Q^2.



G_{En} Results



Two Modern Methods:

1) Polarization Observables

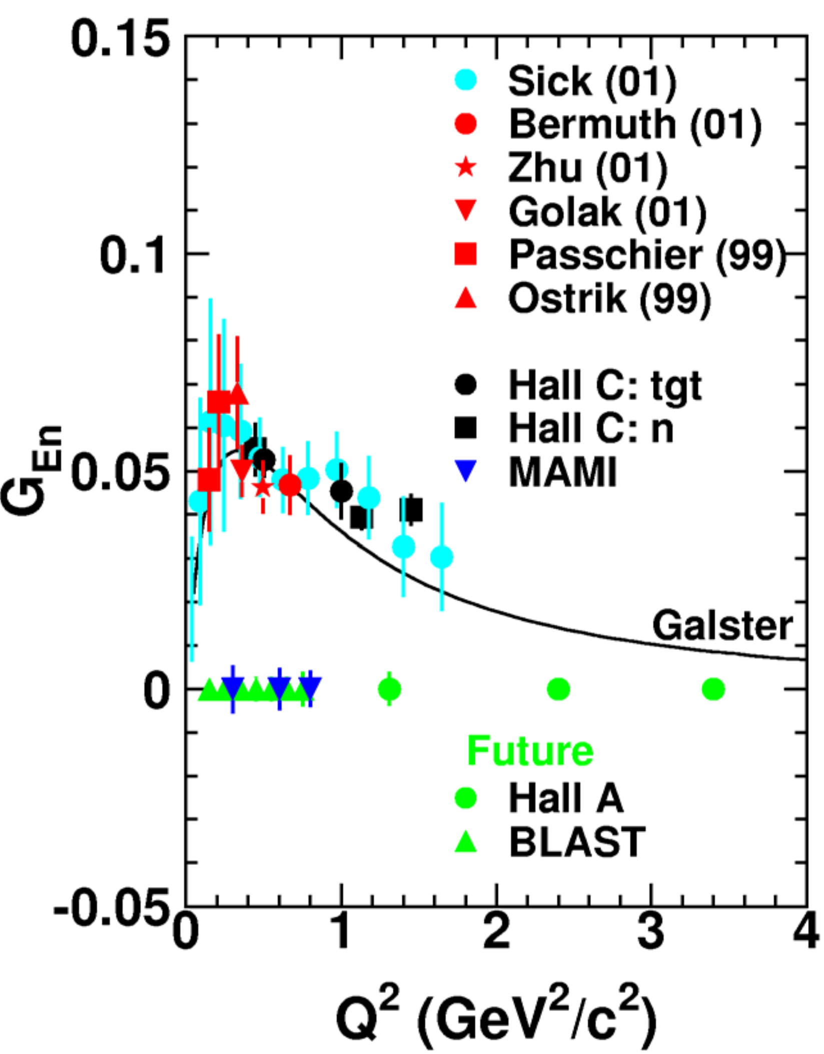
$$\vec{D}(\vec{e},e'n)p$$

$$\overrightarrow{{}^3He}(\vec{e},e'n)pp$$

$$D(\vec{e},e'\vec{n})p$$

2) Extraction from deuteron quadrupole form factor F_{C2}.

G_{En} Future



One experiment (MAMI) is completed and in analysis

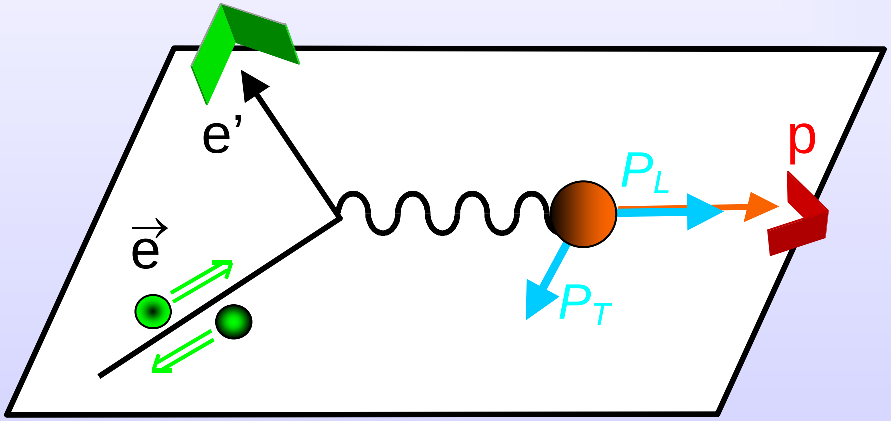
Polarization measurements planned in:

- Hall A: polarized ^{3}He up to Q^2=3.4
- BLAST: precision measurements up to Q^2=0.9

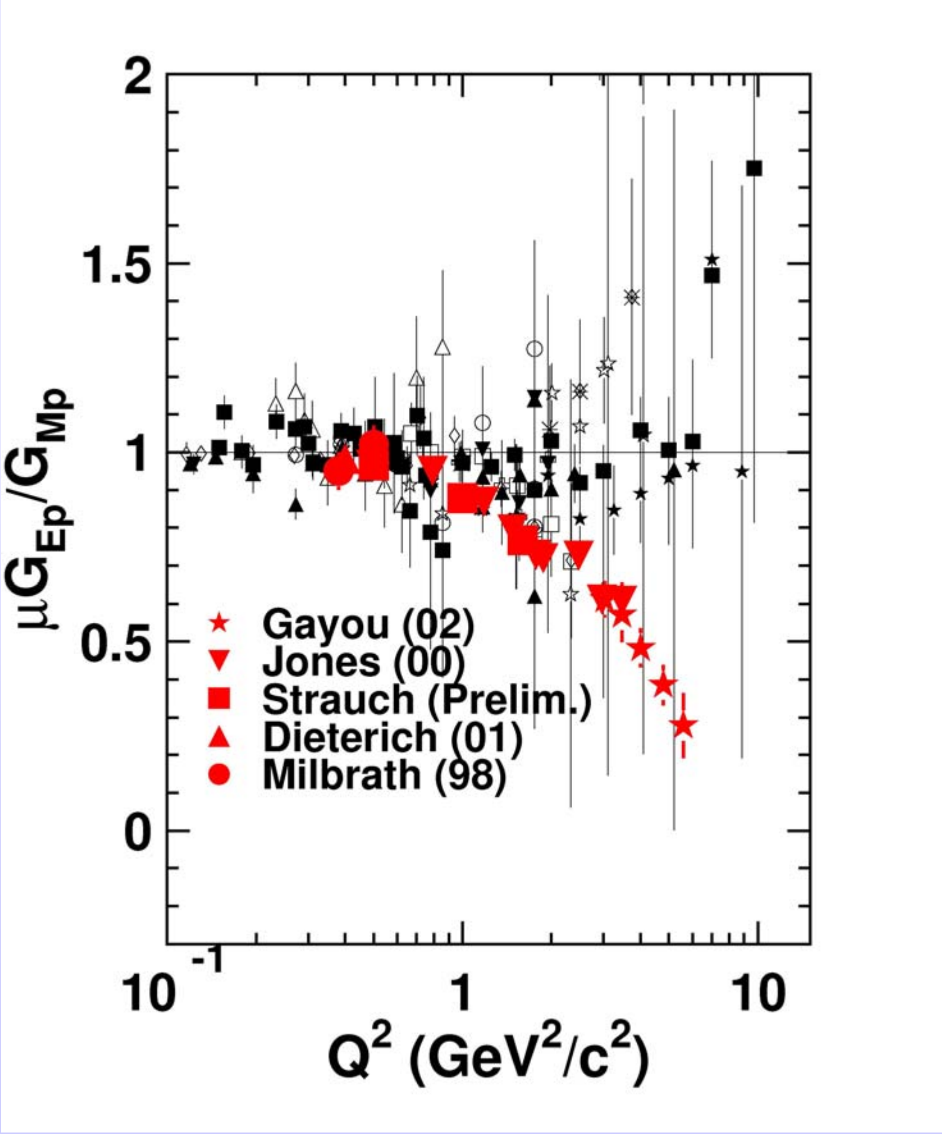
G_{Ep} Results

Recoil Polarimetry

Measure ratio of polarization transferred to proton



$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_T}{P_L}\frac{(E+E')}{2m}\tan\frac{\theta_e}{2}$$



G_{Ep} Future

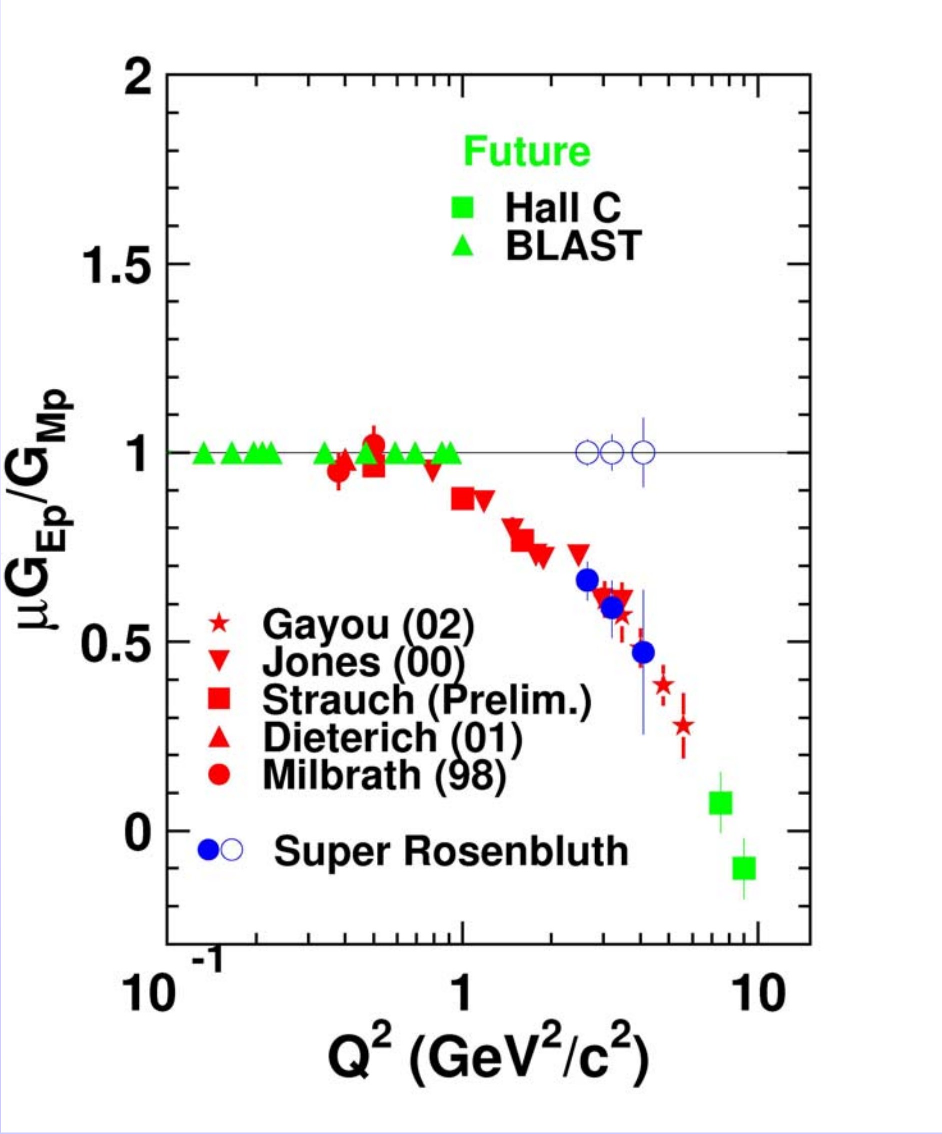
- Super Rosenbluth separation experiment is completed and in analysis.

- Another recoil polarimetry experiment at high Q^2 in Hall C.

- Precision polarized target experiment with BLAST.

- Rosenbluth measurement from data taken in Hall C of JLab.

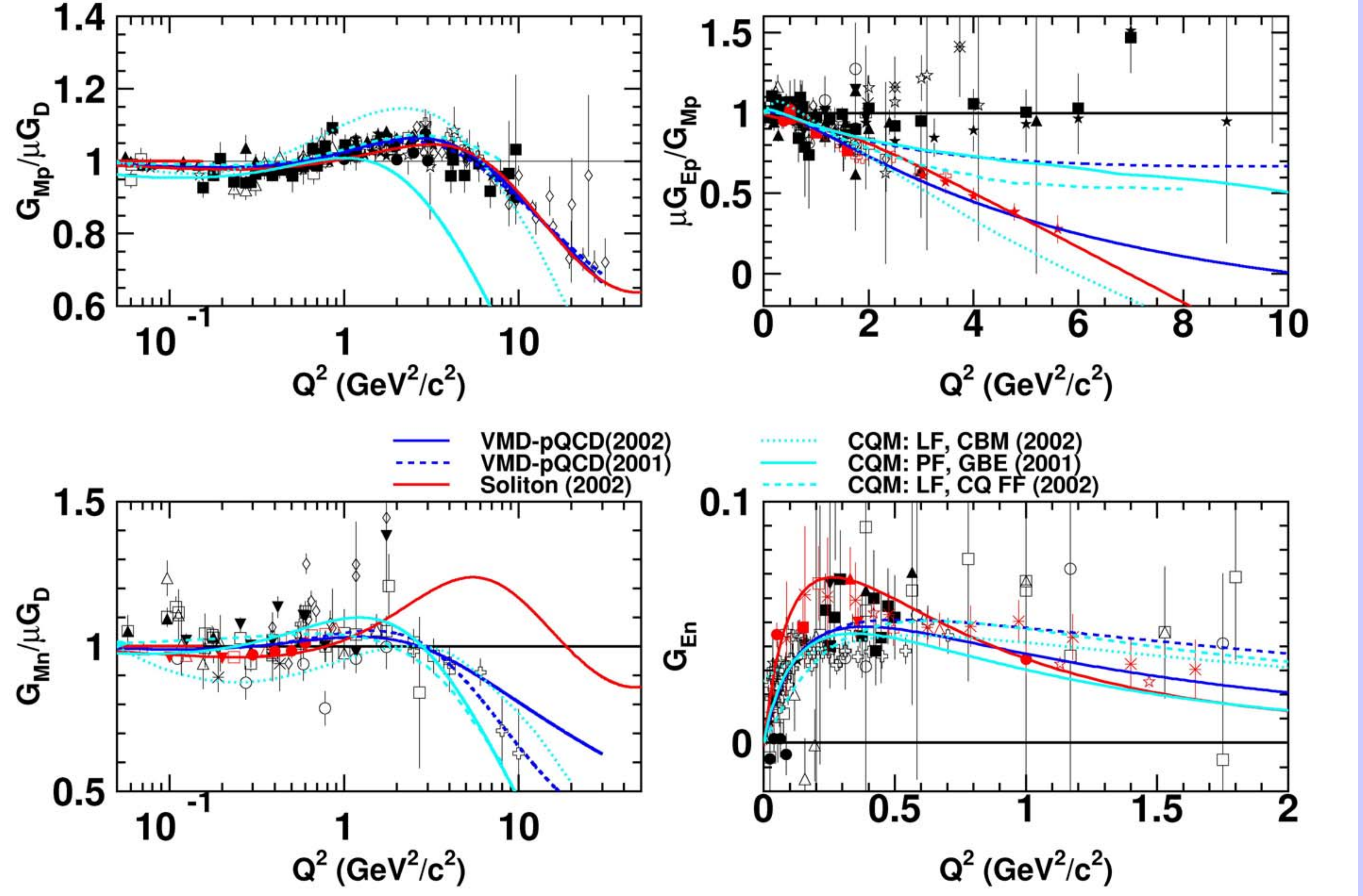
Talks on each of these experiments will be presented today.



Physics Models

- pQCD - high Q^2: Q^2 dependence
  - $G_M = F_1+F_2$, $G_E = F_1-\tau F_2$; $F_1 \sim Q^{-4}$, $F_2 \sim Q^{-6}$.
- Hybrids - combine Vector Meson Dominance at low Q^2 and pQCD at high Q^2.
- Lattice QCD Calculations.
- Relativistic Quark Models vary on:
  - address relativity
  - dynamics

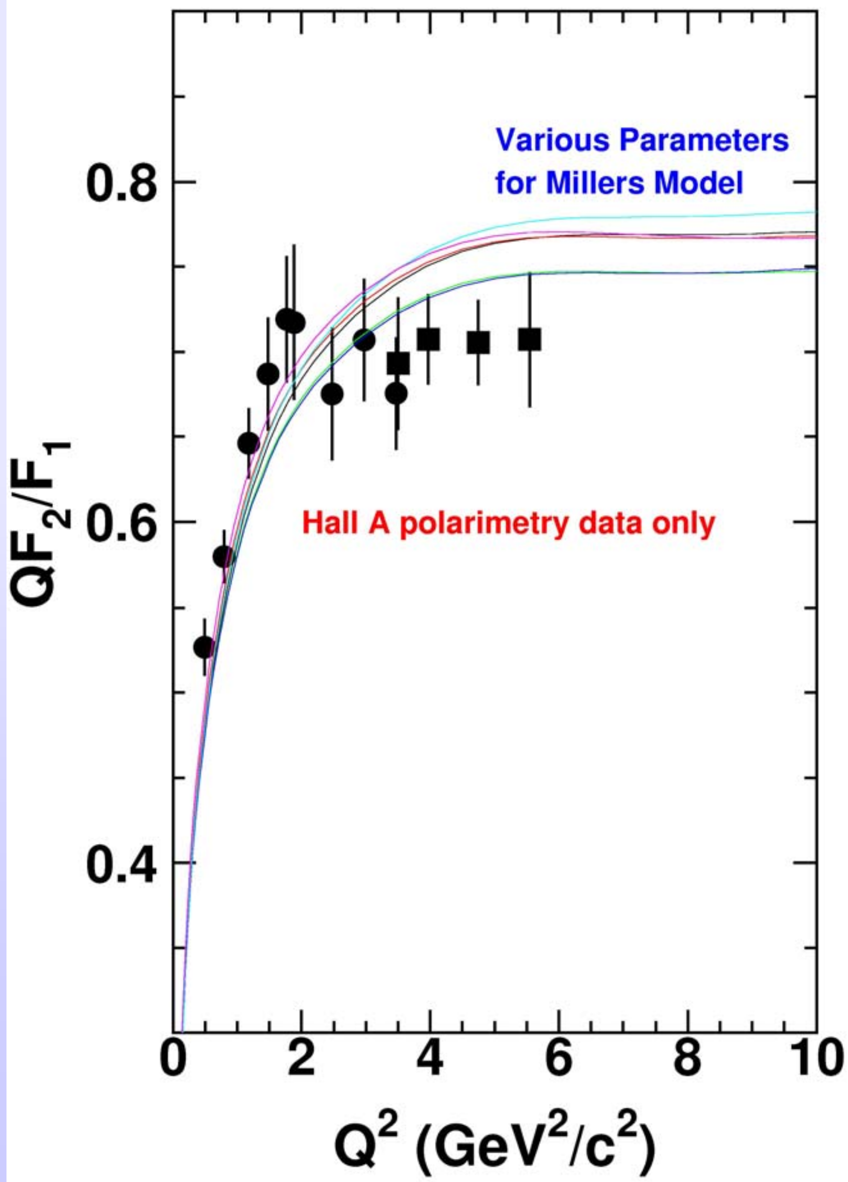
Models



$G_{Mp}/\mu G_D$
$\mu G_{Ep}/G_{Mp}$
$G_{Mn}/\mu G_D$
G_{En}
Q^2 (GeV^2/c^2)
VMD-pQCD(2002)
VMD-pQCD(2001)
Soliton (2002)
CQM: LF, CBM (2002)
CQM: PF, GBE (2001)
CQM: LF, CQ FF (2002)

$Q\,F_2/F_1$

- Recall from pQCD expect $F_2/F_1 \sim 1/Q^2$
- Explanations:
  - OAM breaks helicity conservation (Ralston).
  - Higher twist contributions lead to log terms in F_2/F_1 (Brodsky).
  - Need OAM for spin-flip of massless quark which leads to log terms in F_2/F_1 (Belitsky).
  - Relativistic model leads to terms in lower spinor components (eqv. To OAM) (Miller).



Rosenbluth vs. Polarimetry

What explains the difference between these two experimental results?

- Rosenbluth Separation
  - Data shown to be consistent
  - Very difficult measurements in high Q^2
  - Leading explanation: 2γ exchange which is ε dependent.
    - **Shown to explain half the difference when include elastic contributions only.**

- Polarimetry:
  - probably less susceptible to radiation issues since directly measure G_E/G_M.
  - Experimental technique is robust.

WARNING: Be careful mixing cross section and polarimetry results because they may be measuring different quantities.

Much of second part of this symposium is devoted to this issue.

Strangeness

- EM current

$$\langle N | J_\mu | N \rangle = \bar{U}\left[\gamma_\mu F_1 + i\sigma_{\mu\nu} q^\nu \frac{F_2}{2M}\right] U$$

- Neutral current

$$\langle N | J_\mu^{NC} | N \rangle = \bar{U}\left[\gamma_\mu F_1^Z + i\sigma_{\mu\nu} q^\nu \frac{F_2^Z}{2M} + \gamma_\mu \gamma_5 G_A^Z\right] U$$

- We can define a $G_{E,M}^Z$ analogous to $G_{E,M}^{p,n}$. Assuming isospin invariance, we can define strange form factors

$$G_{E,M}^s = \left(1 - 4\sin^2\theta_W\right) G_{E,M}^p - G_{E,M}^n - G_{E,M}^Z$$

Strange Experiments

- Consider PV e-p scattering, the asymmetry is

$$A_{PV} \propto \varepsilon G_E^Z G_E^p + \tau G_M^Z G_M^p - \left(1 - 4\sin^2\theta_W\right) f(\tau,\varepsilon) G_A^e G_M^p$$

- Need three different measurements to separate G^Z's, and must consider different targets, radiative corrections, ...
  - SAMPLE I,II, III: H, D at backward angles for Q^2 = 0.1, 0.038
  - HAPPEX I,II,III: H, ^{4}He at forward angles for Q^2 = 0.48, 0.10
  - PVA4: H at forward angles for Q^2 = 0.23, 0.10
  - G_0: H,D at forward and backward angles for Q^2 = 0.1-1.0

    - Each of these takes a different experimental approach

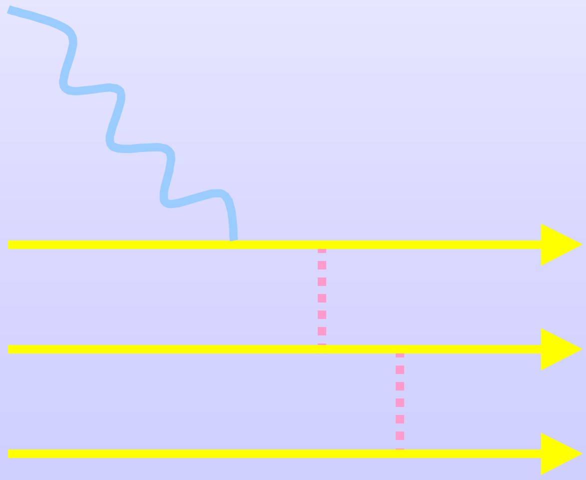
Summary

- Tremendous advance in experimental results in last several years for EM form factors.
  - Convergence in G_{En} and G_{Mn}
  - Models doing a respectable job
- G_{Ep}/G_{Mp} controversy continues
  - 2γ radiative corrections?
  - Implications for “delicate” Rosenbluth separations?
  - importance of orbital angular momentum in relativistic models
- Extremely healthy experimental and theoretical progress in neutral current results.
- In a few more years, we will have more data to continue to whet our appetites.

Asymptotic Dependence

pQCD predicts the asymptotic dependence of F_1 and F_2

- $1/Q^2$ per gluon line
- $1/Q^2$ per helicity flip



- $F_1 \sim 1/Q^4$
  - two gluon exchange,
- $F_2 \sim 1/Q^6$
  - two gluon exchange
  - helicity flip

as $Q^2 \rightarrow \infty \Rightarrow$

- G_E and $G_M \sim 1/Q^4$
- $G_E/G_M \sim 1$

G_{Ep} Analysis

- Brash *et al*. reanalyzed cross section data to extract G_{Mp} assuming G_{Ep}/G_{Mp} fall-off.
  - New parameterization with slightly larger G_{Mp}
  - G_{Mp} results more consistent than published data
- J. Arrington examined cross section experiments
  - no one experiment has significant impact on result.
  - G_{Mp} results more consistent when assume constant G_{Ep}/G_{Mp}.
  - normalization errors cannot cross section result.
  - Cross section measurements are consistent with each other.